THE TRANSFORMATION OF HURRICANE FLOSSY INTO AN EXTRATROPICAL CYCLONE, SEPTEMBER 25–29, 1956

D. A. RICHTER and E. A. DILORETO
National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

Flossy was the first hurricane of the season to enter the United States. While it is interesting to study this storm as a destructive hurricane, this paper is intended instead to show its transformation from a tropical to an extratropical cyclone, its retardation by a building surface anticyclone over southeastern Canada, and its eventual filling and more rapid movement northeastward over the Atlantic Ocean.

Some special attention is given to the explanations and theories concerning the sharp curvature of Flossy's track and the orographical precipitation directly associated with the storm.

2. ANTECEDENT CONDITIONS

A tropical depression was first detected as having a definite circulation over the Yucatan Peninsula on September 21, 1956 [13]. The storm moved north-northwestward across the Gulf of Mexico and reached hurricane intensity on September 23, when it was centered 125 miles south of the Louisiana coast.

Meanwhile, a low pressure system was moving across the Great Lakes region (not shown) with a cold front extending southwestward through the middle Mississippi Valley and the South-Central Plains region. The corresponding 500-mb. pattern on September 23 (not shown) accompanying the surface Low had a cyclonic center located near The Pas, Manitoba, with a trough extending southward through Minnesota and Iowa.

As Flossy approached the Gulf Coast on September 24 (fig. 1A), the Great Lakes low pressure center moved east-southeastward to eastern New York with the cold front advancing to the eastern Appalachians and extending southward to northern Alabama. The associated 500-mb. trough (fig. 1B) extended southward over the Ohio Valley. The corresponding 1,000–500-mb. thickness chart (fig. 1C) shows negative departures from normal of 200–400 feet following the front.

3. RECURVATURE

It can be seen from figure 1C that, in the southeastern United States, thickness values were below normal to the north of 29° N. and above normal over the Gulf of Mexico to the south. As Flossy approached Louisiana, the juxtaposition of the pure tropical air accompanying the hurricane and the cool modified air to the north caused the thermal gradient to increase, thereby making a stronger barrier for a northward-moving storm to penetrate. As the hurricane was not of such severe proportions as to destroy this thermal field and continue moving northward, it both made an almost 90° turn to the right just north of Burrwood, La., and began to fill soon after crossing the shoreline.

Not to be overlooked as a possible contributing factor to Flossy's recurvature is the frictional effect. Since the angular deviation of the wind from the isobar increases with the roughness of the underlying surface (Petterssen [9]), it follows that as the hurricane neared the Gulf Coast there was a great amount of cross-isobaric flow caused by increased friction due to air flowing over the rougher land from over the water. This convergent zone tended to "pile up" the air along the coast, thus at least retarding its northward movement. It is difficult to contemplate quantitatively just how much this affected the actual veering.

Examination of the 700–500-mb. mean temperatures (not shown) makes it readily evident that the sharp curvature of the hurricane to the right was in accord with the warm tongue steering principle (Simpson [11]). However, the degree of curvature of this particular storm was slightly more than this steering method indicated.

Still another forecasting tool used to some extent is a method offered by Cline [5] which moves a hurricane along an axis of maximum precipitation intensity. He concluded that in tropical cyclones which curved to the right, the greatest hourly rainfall intensity was farther to the right of the line along which the cyclonic center was advancing at the time. Although we had but limited reporting stations along the coast, it appears that the maximum precipitation was to the right of an instantaneous track of the moving hurricane (fig. 9). After recurvature, Flossy moved approximately in a straight line toward the region of the greatest precipitation intensity (fig. 10).

4. RETARDATION

As the 500-mb. trough that was associated with the

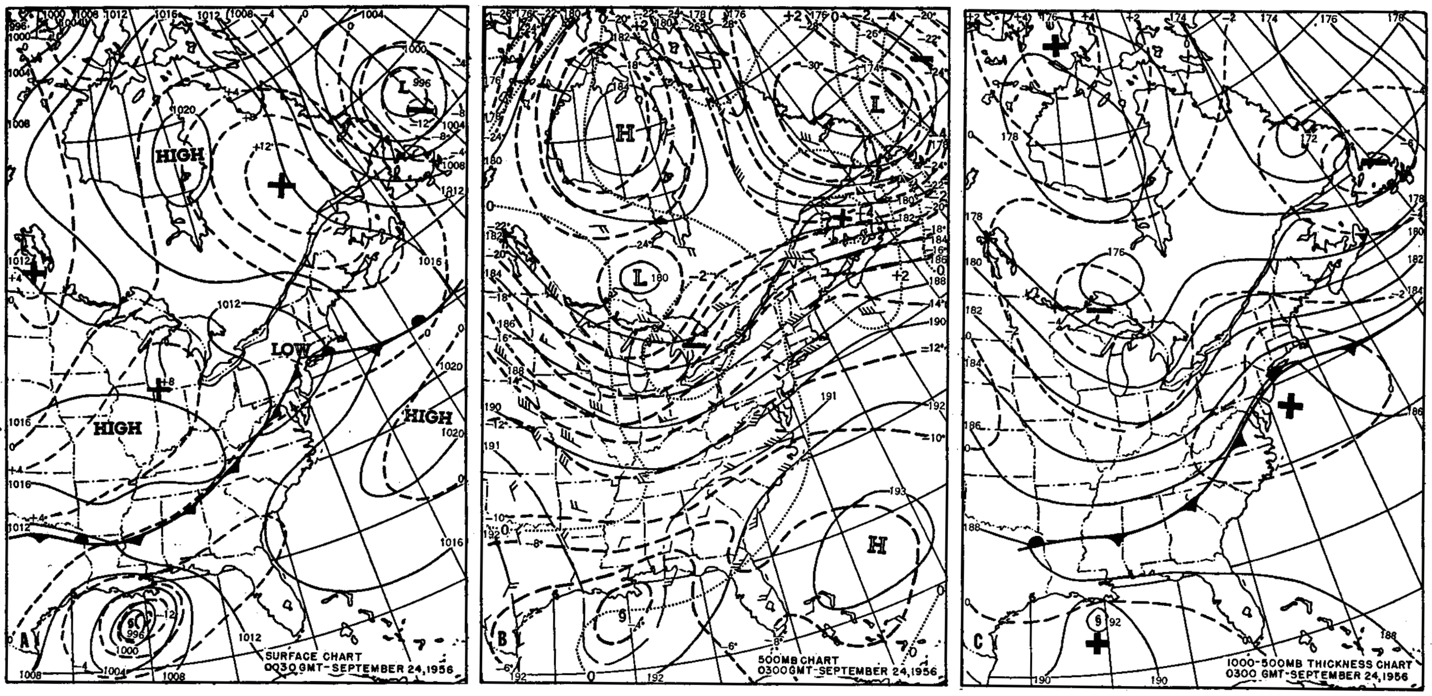

FIGURE 1.—September 24, 1956. (A) Surface chart for 0030 GMT, with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT. Contours (solid lines) are labeled in hundreds of geopotential feet. Superimposed are the 500-mb. 12-hour height changes (dotted lines) in hundreds of feet. (C) 1000–500-mb. thickness chart for 0300 GMT. Thickness (solid lines labeled in hundreds of feet) is proportional to mean virtual temperature. Superimposed are the 1000–500-mb. departures from normal (dashed lines).

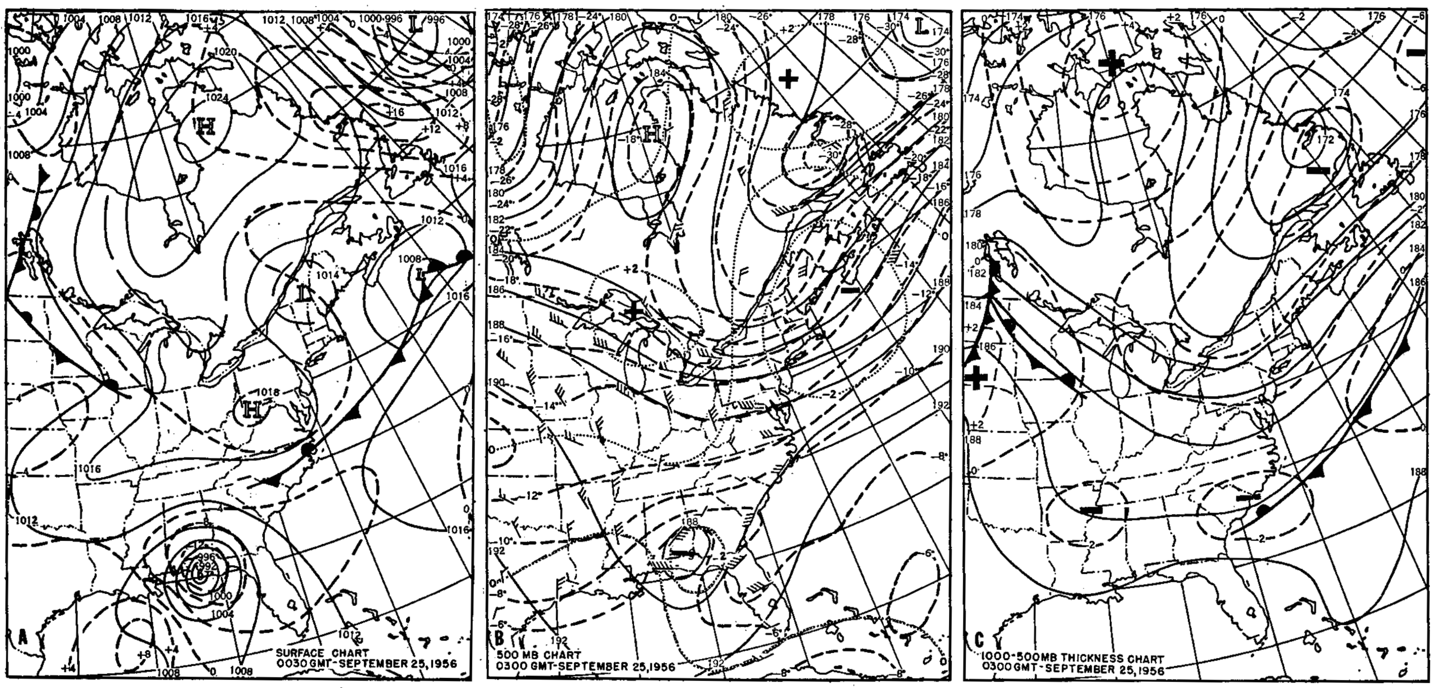

FIGURE 2.—September 25, 1956. (A) Surface chart for 0030 GMT with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

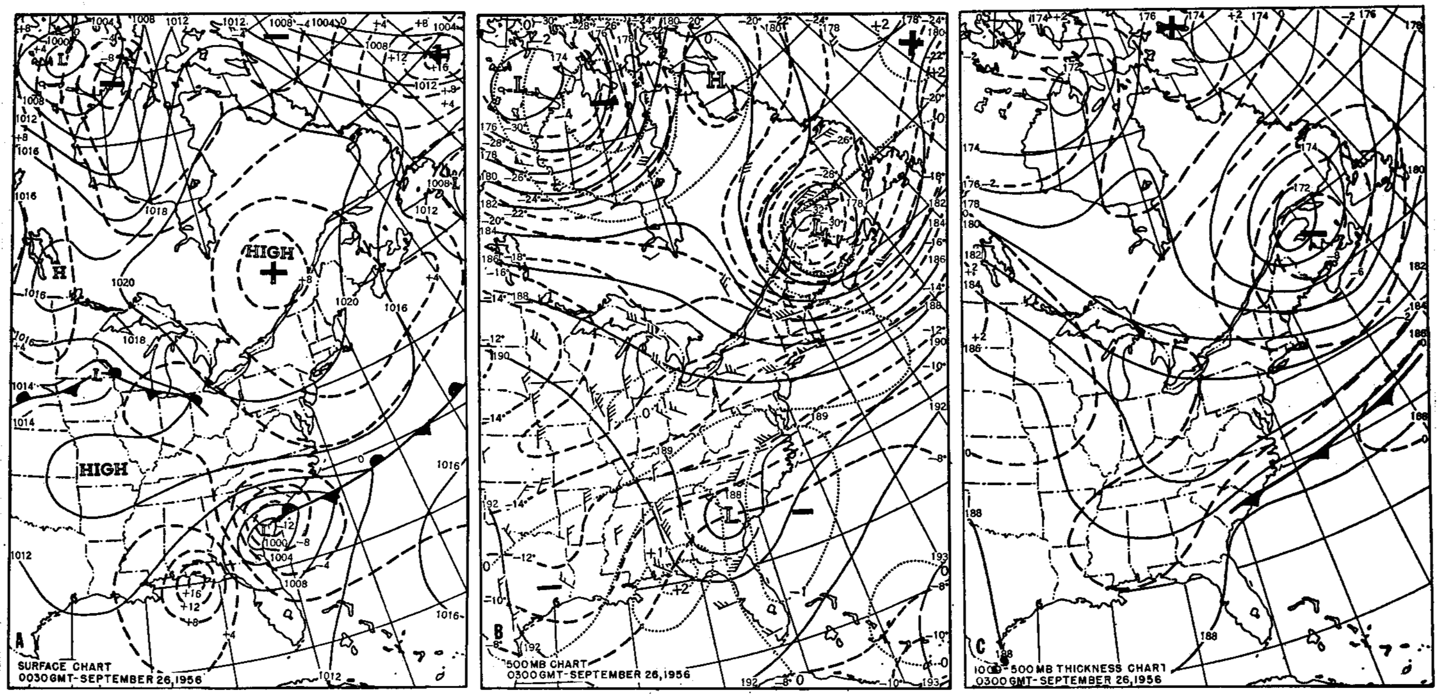

FIGURE 3.—September 26, 1956. (A) Surface chart for 0030 GMT with 24-hour pressure changes (dashed lines) superimposed. (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

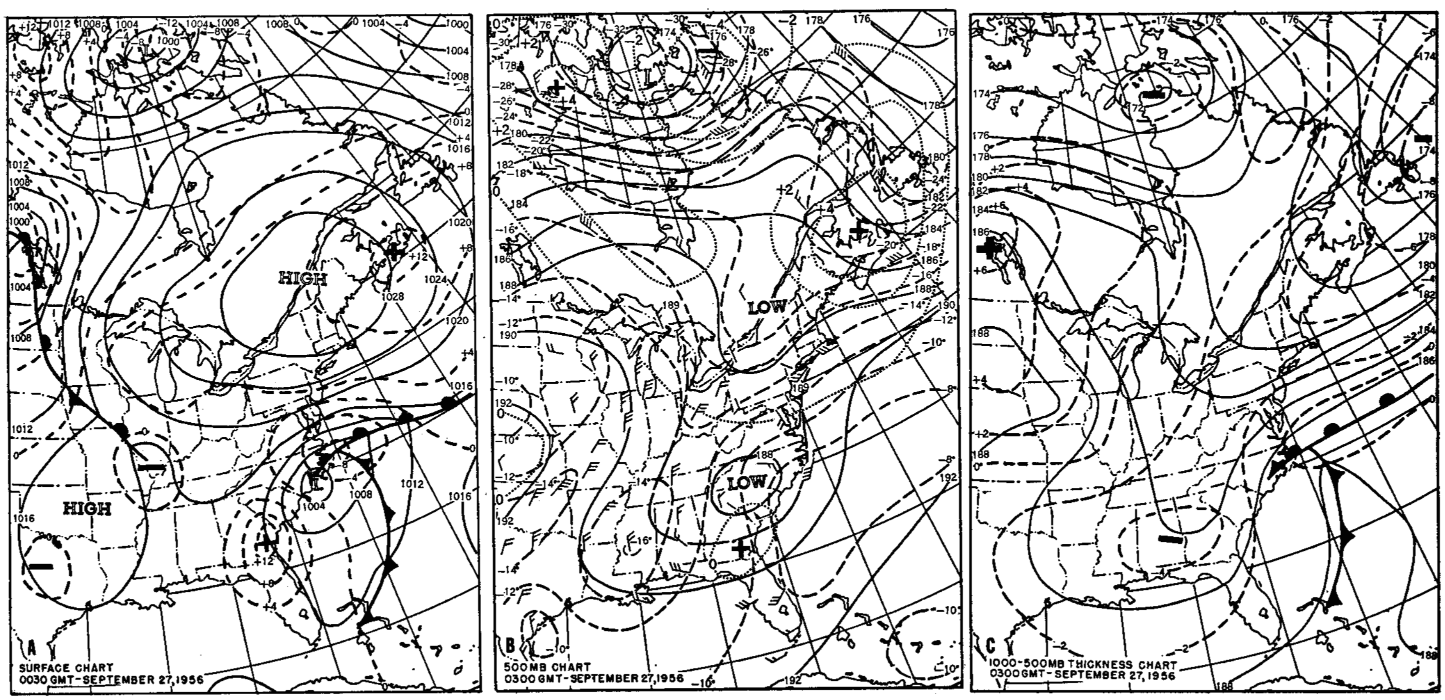

FIGURE 4.—September 27, 1956. (A) Surface chart for 0030 GMT, with corresponding 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height changes (dotted lines) superimposed. (C) 1000–500-mb. thickness chart for 0300 GMT, with superimposed 1000–500-mb. thickness departures from normal (dashed lines).

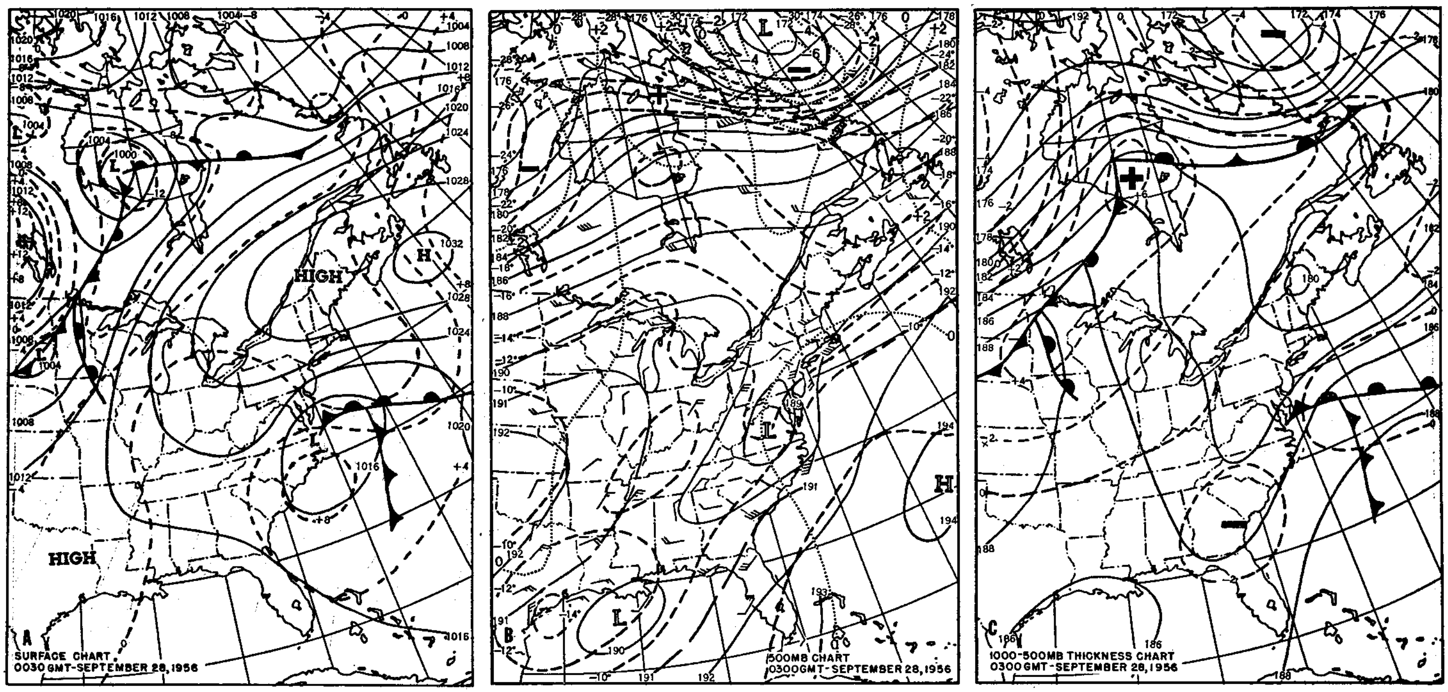

FIGURE 5.—September 28, 1956. (A) Surface map for 0030 GMT, with 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with corresponding 12-hour 500-mb. height change (dotted lines). (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

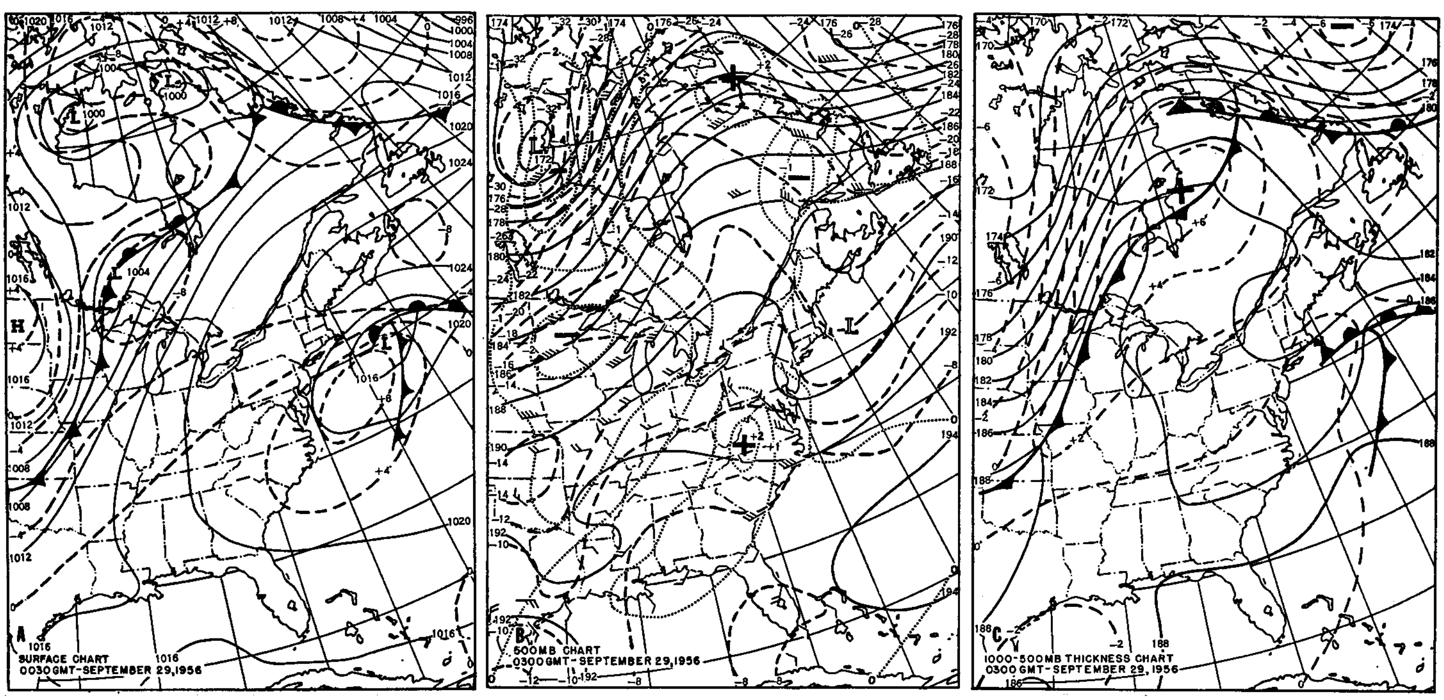

FIGURE 6.—September 29, 1956. (A) Surface chart for 0030 GMT, with associated 24-hour pressure change (dashed lines). (B) 500-mb. chart for 0300 GMT, with 12-hour 500-mb. height change (dotted lines) overlaid. (C) 1000–500-mb. thickness chart for 0300 GMT, with 1000–500-mb. thickness departures from normal (dashed lines) superimposed.

surface Low moving through New York State came directly in a north-south line with the trough formed by Flossy, it was thought possible by some forecasters that the storm would get caught in the westerlies (cf. Riehl [10]) and move rapidly northeastward. Examination of consecutive 500-mb. charts of September 24–26 (figs. 1B, 2B, 3B) shows that the northern part of the trough moved faster than the southern, giving it a northeast-southwest tilt by the 26th. Height rises following the northern section of the trough bridged across the New England States, thus disconnecting the tropical Low from the zonal flow pattern and, in effect, cutting it off.

The southern trough then decelerated with an associated retardation of the eastward component of Flossy's movement. A qualitative discussion of some of the dynamical factors effecting this deceleration will be helpful in understanding this occurrence.

A thermal trough extending southwestward from an easterly-moving low center at 500 mb. over northwestern Canada had by 0300 GMT, September 25 (fig. 2B) been advected over the Dakotas. The difluent wind field (Bjerknes [3]) over this area effected a slight cross-contour flow southward so that 24 hours later, 0300 GMT September 26 (fig. 3B), a pronounced thermal trough extended from the Great Lakes area to southeastern Colorado. The corresponding 1000–500-mb. thickness chart (fig. 3C) indicated a thermal ridge in this position. Inspection of the 1000–700-mb. thickness chart (not shown) for the same time shows an even more pronounced thermal ridge. However, a 700–500-mb. thickness field (not shown), derived by graphical subtraction, was found to have a thermal trough in a position that compared favorably with the temperature field at 500 mb. It can then be concluded that all the cooling took place above the 700-mb. level with warming in the lower layers.

On September 27 (fig. 4B), the advection of thermal vorticity from the northwest, together with the absence of any anticyclonic vorticity in the contour field west of the trough, induced small 500-mb. height falls over the lower Mississippi Valley. At the same time the surface isobaric features prevented the southeastward propagation of the low-level warm tongue while the cold air at 500 mb. had nothing to obstruct its southeastward transport. This occurrence allowed the thermal trough aloft to come into phase with and reinforce the already-existing 1000–500-mb. thickness cold trough of the Appalachians (fig. 4C).

Sutcliffe and Forsdyke [12] point out that the center of surface vorticity tends to develop in the direction of and with a speed proportional to the thermal wind. They mention that the area just ahead of the thermal trough line is favorable for cyclogenesis with anticyclogenesis favored to the rear. The advection of thermal vorticity from the west served in this case to retard the 1000–500-mb. thermal trough. Figure 4C shows a general broadening of the southern portion of the trough, actually shifting the mean position westward. The subsequent two thickness charts (figs. 5C and 6C) show a split in the thermal field. A cold pool moved southwestward out over the Gulf of Mexico and the thermal trough associated with Flossy drifted northeastward.

While these events were transpiring in the middle latitudes, a blocking 500-mb. High over Hudson Bay (fig. 1B) was moving eastward as strong cyclonic vorticity advection emanated from a Low north of Fort Nelson. Horizontal mass-divergence in the forward half of this difluent trough resulted from the maintenance of the maximum wind velocities to the rear of the trough line. The air parcels moving through the trough were therefore subjected to continual deceleration and hence were directed outward toward higher heights. This difluent process had the effect of lowering heights considerably faster to the rear of the High than they were rising to the east of it (figs. 2B and 3B) and consequently of elongating the ridge and weakening it slightly. This in turn caused the ridge to become dynamically unstable (Bjerknes [4]); that is, when the curvature in the contour pattern of the anticyclonic flow approached the critical curvature for the strength of the gradient, the air was unable to make the sharp curve over the top of the crest of the ridge and was therefore compelled to cross contours toward lower heights (Wobus [14]). The development of over-shooting supergradient winds on the downstream side of the ridge resulted in the formation and advanced position of a new ridge north of Laborador (fig. 3B), and consequently in the veering of winds in that area to a northeasterly direction.

Further examination of the overall picture shows that on September 24 (fig. 1A), a cold Low moved eastward off the Laborador coast. While the main centers both at the surface (fig. 2A) and aloft (fig. 2B) proceeded uneventfully eastward, a pocket of cold air remained behind at upper levels near Goose Bay, Labrador. The 1000–500-mb. thickness chart on September 25 (fig. 2C) shows values greater than 600 feet below normal. During the next 24 hours, the aforementioned 500-mb. ridge advancing with its northeasterly winds transported this cold air southwestward to the Gulf of St. Lawrence (fig. 3B). In this area the 1000–500-mb. thickness on September 26 (fig. 3C) was greater than 800 feet below normal.

Continued southeastward movement of the ridge and its accompanying warm air advection forced the cold trough eastward out of the coastal area. Comparison of the height values of the 500-mb. charts of September 26 and September 27 (figs. 3B and 4B) with those of the 1000–500-mb. thickness charts of the same period (figs. 3C and 4C) in the Nova Scotia area, shows that while the thickness change was only plus 250 feet, the 500-mb. height change was plus 550 feet, a difference of 300 feet. This 300-foot addition to the 500-mb. height was revealed in a 12-mb. rise in surface pressure (fig. 4A) over Nova Scotia. Similarly comparison of the same sets of charts with corresponding changes in these charts shows that in the area north of New England a plus 150-foot difference

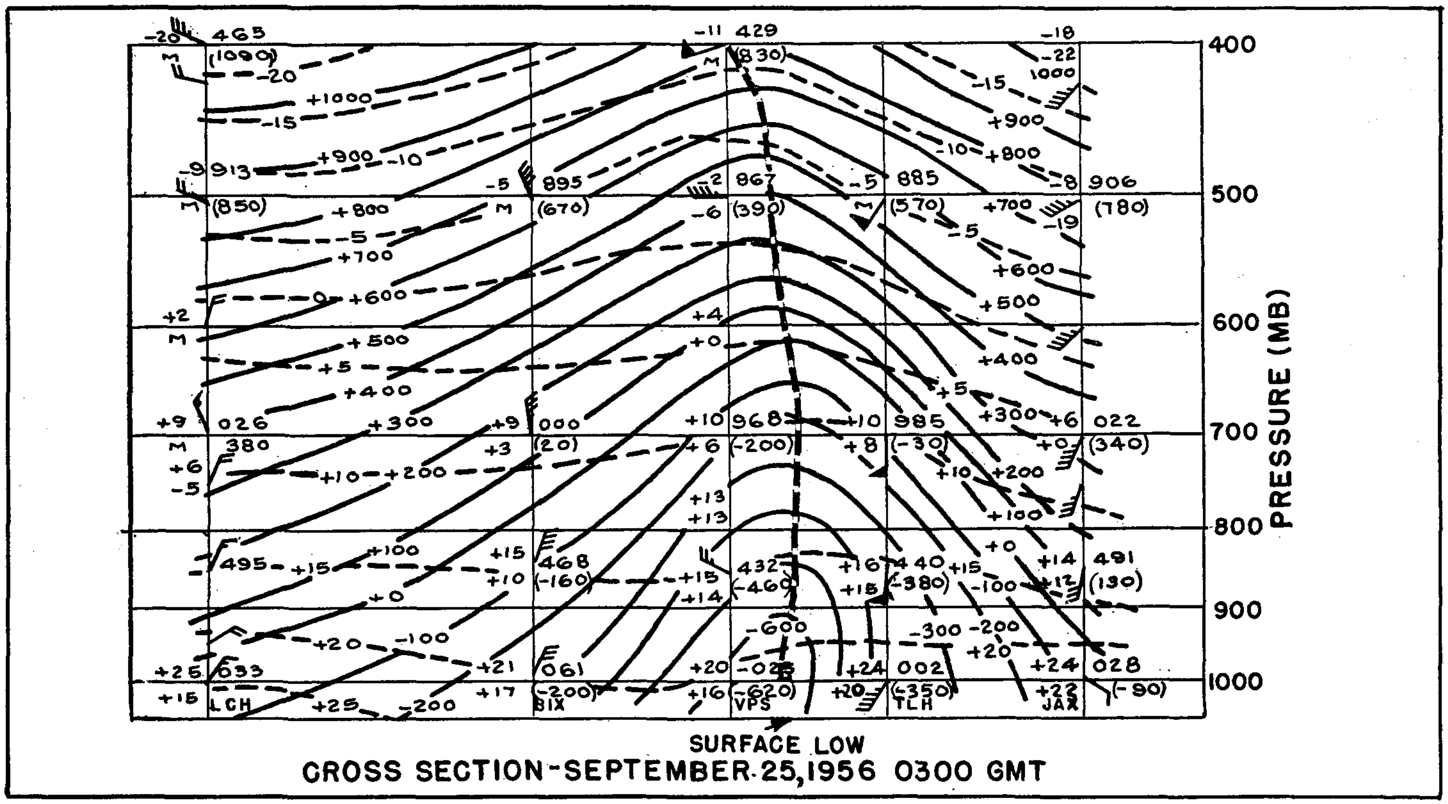

FIGURE 7.—Vertical cross section through center of hurricane on September 25, 1956, 0300 GMT. Figures in parentheses are departure from standard atmosphere using as the standard base: 1000 mb. = 370 ft., 850 mb. = 4, 780 ft., 700 mb. = 9,880 ft., 500 mb. = 18,280 ft., and 400 mb. = 23,560 ft. D-factor isolines (departures from standard atmosphere) are indicated in hundreds of feet (solid lines). Isotherms (dashed lines) are for intervals of 5° C. Heavy dashed line shows the center of the core axis. LCH = Lake Charles, La., BIX = Biloxi, Miss., VPS = Valparaiso, Fla., TLH = Tallahassee, Fla., and JAX = Jacksonville, Fla.

between the thickness and 500-mb. charts existed. This was directly related to a 7-mb. increase in the intensity of the surface High.

The most significant result of the previously discussed synoptic conditions was the development of strong low-level easterly winds along the Mid-Atlantic States. The surface charts of September 24–27 (figs. 1A, 2A, 3A, and 4A) show that the zero isallobar of the 24-hour pressure changes was practically stationary over the State of Virginia throughout this entire period. During that same 72-hour interval, the pressure at Albany, N. Y. rose from 1010 mb. to 1028 mb., while at Wilmington, N. C., as the surface Low moved northeastward, pressures fell from 1017 mb. to 1000 mb. Hence, in view of this 35-mb. increase in gradient and pressure rises to the north, it became very unfavorable for the storm located near the North Carolina coast to advance rapidly in any northerly direction.

On the following day, September 28, the temporarily blocking surface High causing this stagnation was beginning to weaken. A surface Low located near Lake Winnipeg on September 27 and moving northeastward to Hudson Bay on September 28 (fig. 5A) caused strong warm air advection in the northwestern quadrant of the High. A plus 600-ft. 1000–500-mb. thickness departure from normal (fig. 5C) was progressing just in advance of the surface Low. At 500 mb. (fig. 5B), height rises associated with the ridge over the eastern part of Hudson Bay were of much less magnitude than the thickness rises. The effects of this difference were reflected at the surface as pressure falls. Figure 5A also shows that a separate high center had formed east of Nova Scotia in the same general area where, on the previous day, there was a 12-mb. anallobar. The subsequent map (fig. 6A) shows that this became the dominant high center, as the one to its west fell victim to the pressure falls from the northwest and diminished in intensity.

At the same time the remnant of Flossy, while steadily losing strength in central intensity as it moved up the southeastern seaboard, abruptly filled 12 mb. in the 24-hour period of September 27–28 (figs. 4A, 5A). This filling may also be detected by comparing sets of values of the 500-mb. heights and 1000–500-mb. thicknesses. It can best be explained by the fact that the upper-air divergence and cyclonic vorticity over the storm were too weak to compensate for the sum of frictional and inertial convergence in the low layers. Concurrently, the winds aloft were too light to transport the colder air from the west fast enough to overcome the filling although they were successful in retarding the trough.

On September 27 (fig. 4B), the thermal trough previ-

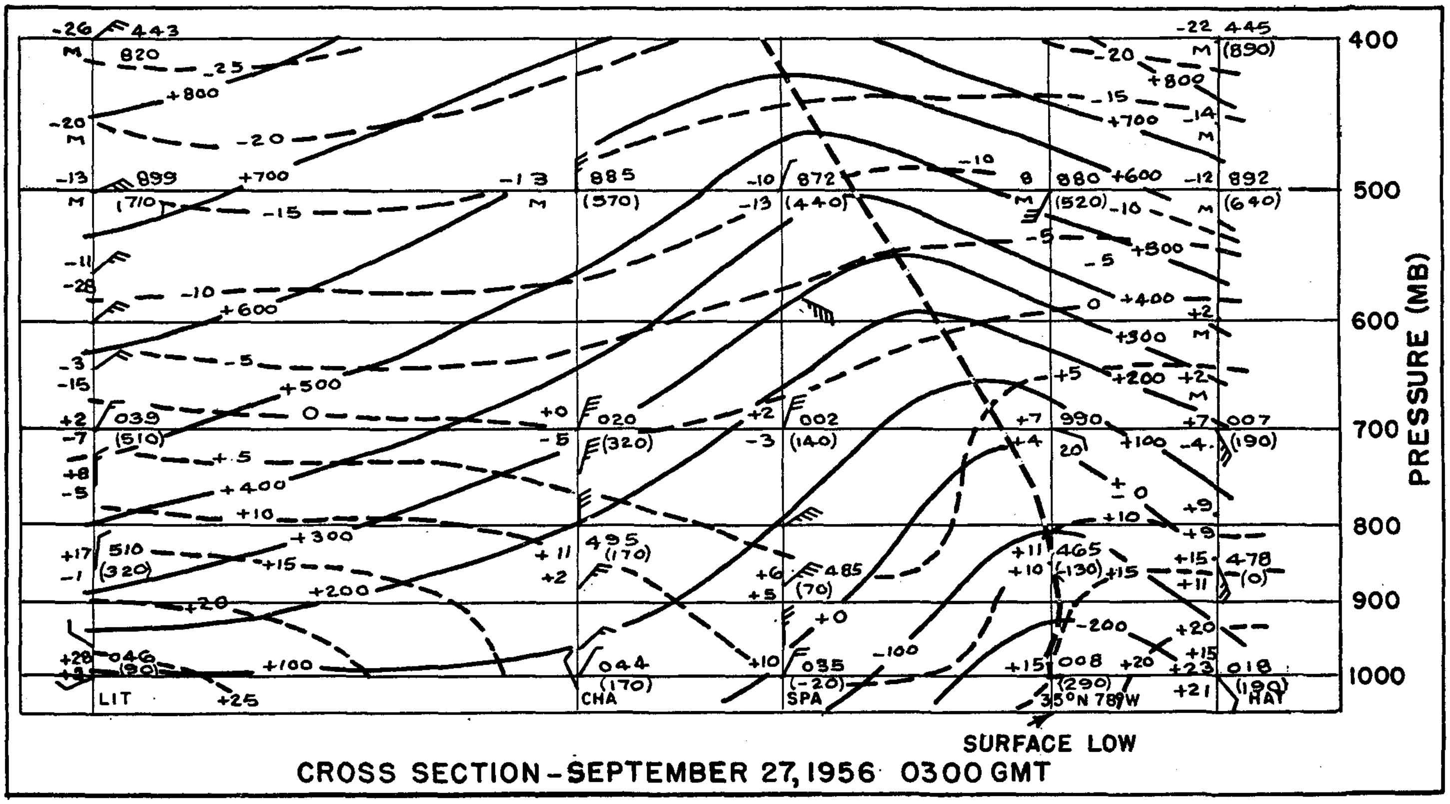

FIGURE 8.—Vertical cross section through center of Low, 0300 GMT, September 27, 1956. Note change in slope of trough and the cold air advection in lower levels compared to figure 7. LIT = Little Rock, Ark., CHA = Chattanooga, Tenn., SPA = Spartanburg, S. C., and HAT = Hatteras, N. C.

ously mentioned in the discussion of retardation was over the Ohio River Valley, about 300 miles west of the Low. Twenty-four hours later, on September 28 (fig. 5B), the cold air, which had lowered heights in the rear of the trough, was then in phase with the contours. Meanwhile a warm ridge was advancing southeastward across the Great Lakes. The accompanying anticylconic vorticity and warm air advection ahead of this ridge raised heights over the Low and caused the trough to be displaced eastward (fig. 6B). At the surface, with the High over New England rapidly falling away and the Low near southeastern Virginia weakening considerably, the strong gradient had all but completely vanished. The cyclone then moved somewhat faster northeastward during the next 24 hours to a position just southeast of Nantucket, Mass. (fig. 6A), ending the heavy rains and the threat of high tides along the New England Coast.

5. TRANSFORMATION

The temperature distribution near the surface and up to 700 mb. is quite uniform in a hurricane (Jordan and Jordan [7]). Above 700 mb. the warm-core characteristics become well marked with temperatures in the center averaging as much as 10° C. warmer than the outside. The absence of this characteristic soon after Flossy entered the coast and moved across the Florida Panhandle, indicated that the storm had rapidly begun losing its hurricane structure. Figure 2C shows that the storm was advancing over an area where thickness values were already below normal. As it is probable that a hurricane is maintained by the latent heat energy released from the ascending moist tropical air (e. g. Mohri [8]) it seems that this intrusion of cooler air into the storm circulation effectively reduced the supply of latent heat and thereby caused the storm's degeneration, marked by a decrease in wind speeds. That the dissipation of hurricane winds is controlled primarily by the energy budget, and not by the frictional effect, has been pointed out by Hubert [6].

While it is difficult to determine exactly when the hurricane began to acquire extratropical distinction, cross sections through the center of Flossy (figs. 7 and 8), made 48 hours apart, clearly show differences in structure between the tropical and extratropical cyclone. In figure 7, isolines of departure (D) of pressure altitude from that of the standard atmosphere (Bellamy [1]) on September 25 indicate that a practically vertical core of warmer temperatures was over the center. It is suspected, however, that because of the very slight tilt of the core axis near 500 mb., the hurricane was nearing its last stage as a pure tropical storm.

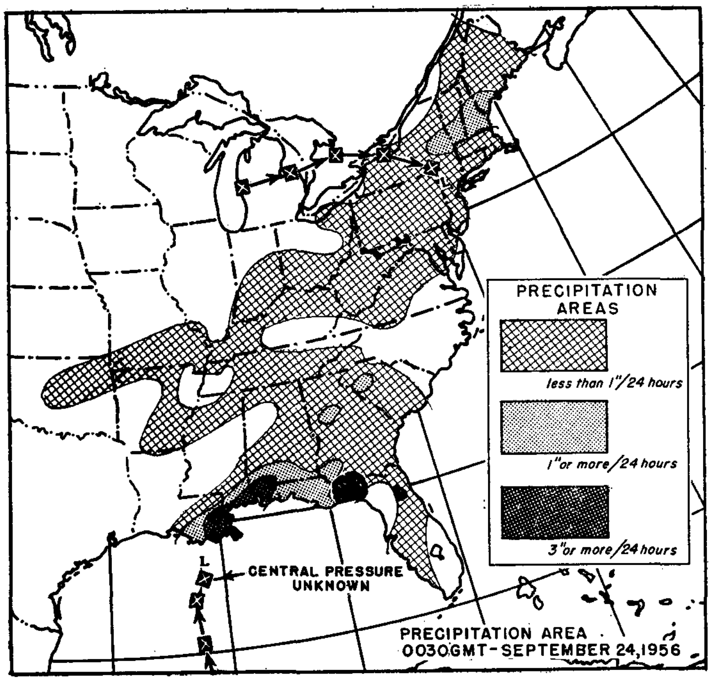

FIGURE 9.—Precipitation for 24-hour period ending at 1230 GMT, September 24, 1956. Small x's indicate storm track at 6-hour intervals.

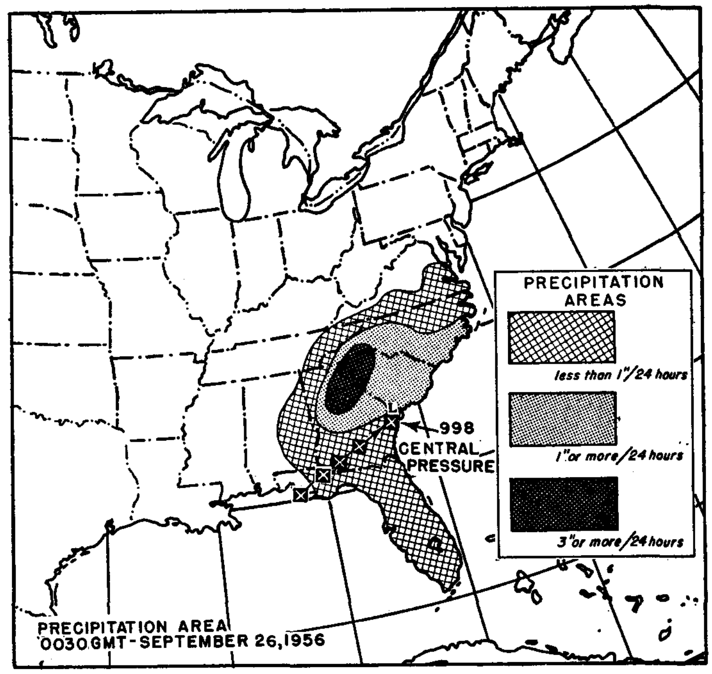

FIGURE 11.—Precipitation for 24-hour period ending at 1230 GMT, September 26, 1956.

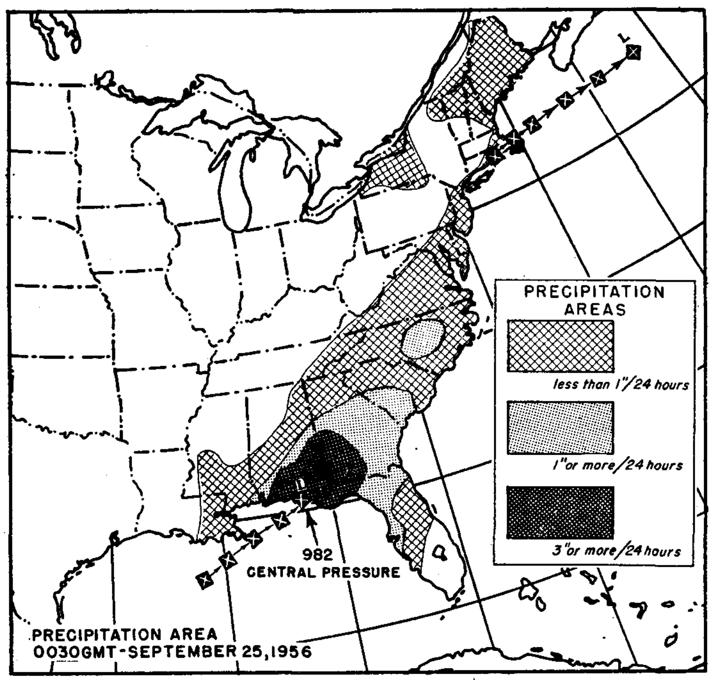

FIGURE 10.—Precipitation for 24-hour period ending at 1230 GMT, September 25, 1956.

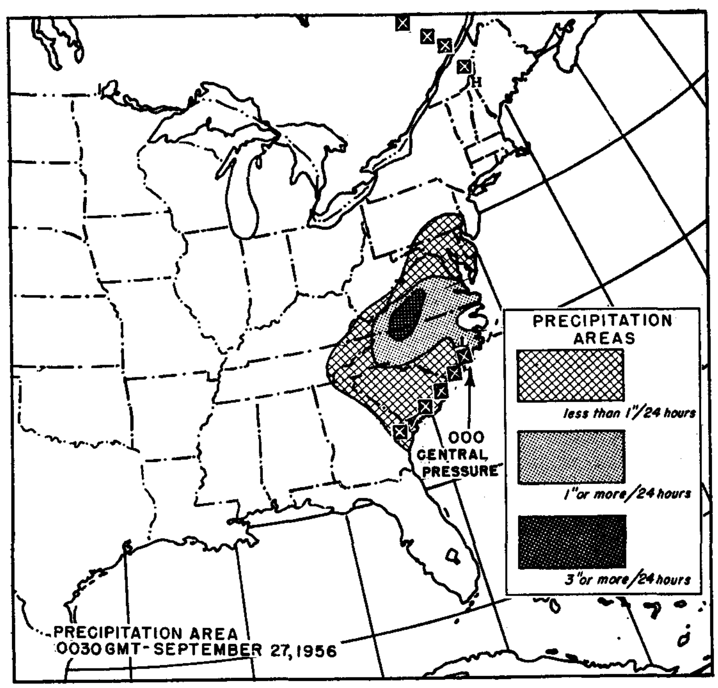

FIGURE 12.—Precipitation for 24-hour period ending at 1230 GMT, September 27, 1956.

The cross section of September 27 (fig. 8), when the storm was centered near Wilmington, N. C., leaves little doubt that Flossy had at that time the extratropical characteristics apparent in many wave patterns. The axis of the Low core, from the surface to the 500-mb. level, then had a definite slope to the west. There was also quite a difference in the thermal field: (1) the 500-mb. temperature over the Low was now 8° C. colder than it was on September 25; (2) strong cold air advection was present below the 700-mb. level west of the Low; and (3) the colder temperatures above the 700-mb. level were advancing eastward toward the Low; this, incidentally, eventually made it a cold Low. The isothermal patterns on the 500-mb. charts of September 25 (fig. 2B) and September 27 (fig. 4B) also clearly demonstrate the structural differences in the types of cyclones.

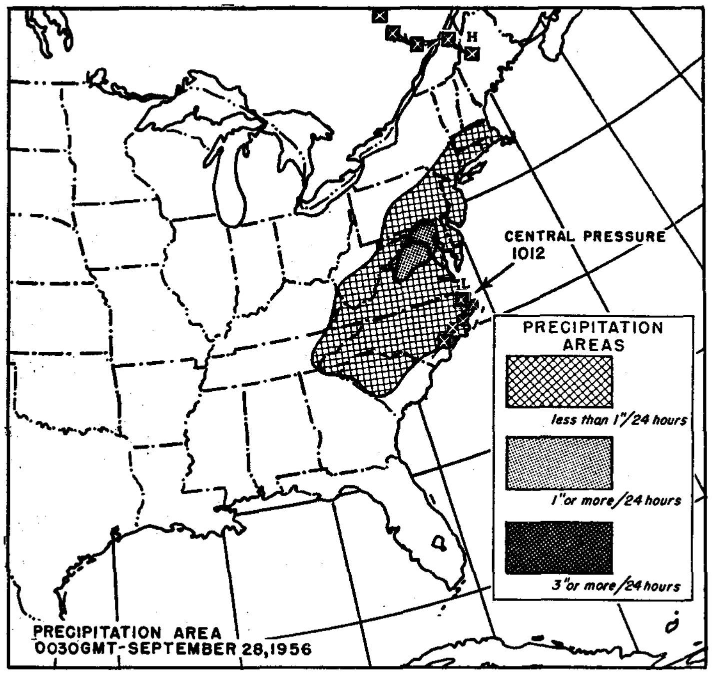

FIGURE 13.—Precipitation for 24-hour period ending at 1230 GMT, September 28, 1956.

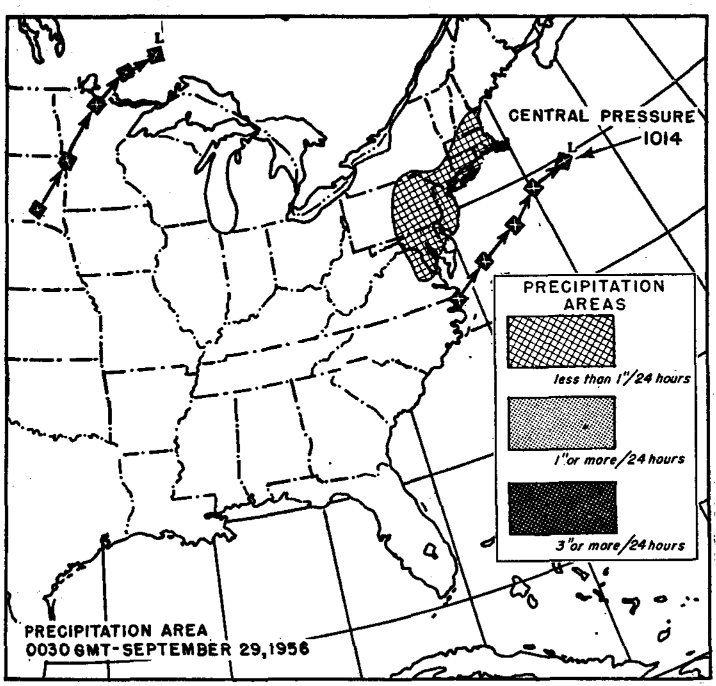

FIGURE 14.—Precipitation for 24-hour period ending at 1230 GMT, September 29, 1956.

6. PRECIPITATION

According to Cline [5], tropical cyclones in the Gulf of Mexico have the greatest precipitation intensity in front of and somewhat to the right of a line along which the storm is moving, with relatively little precipitation in the rear half. This is due, he states, to the winds of high velocity moving through the right rear quadrant and converging with weaker winds having greater cross-isobar components in the right front quadrant. As Flossy with its deep moist layer of unstable tropical air and low condensation level first approached the Gulf Coast, orography became an important factor in determining the overall total precipitation amounts (Bergeron [2]). As the southerly winds forced the tropical air over the colder air near the ground, it did not require much upglide cooling to condense the moisture from the already nearly saturated air.

Figure 9 shows that, as the hurricane neared Louisiana, the heaviest amounts of precipitation were in an area neighboring the coast. The frictional effect previously mentioned in the recurvature discussion was probably most responsible for the 3-inch isohyet found immediately adjacent to the shore. As the cyclonically curved isobars traversed the coast, the winds, due to friction, crossed the isobars at a greater angle toward lower pressure. This added convergent zone increased the upward vertical motion of the air parcels, which in turn caused saturation to occur more rapidly and precipitation to fall more intensely.

On the following day, September 25 (fig. 10), the maximum precipitation area continued to lie directly in front of the hurricane. It is difficult to determine exactly which cause had the most effect in producing this rain; the convergence suggested by Cline, the ascending motion caused by friction, or the general upslope motion of the warm tropical air overriding the colder air over land. All these elements were still present on the 25th.

The areas of rainfall shown in figures 9–14 of course are not synoptic with the indicated centers, but instead cover a 24-hour period beginning 12 hours prior to and ending 12 hours after the surface map time. For all intents and purposes this does not affect the general direction of maximum precipitation, although the extent of the area and the amounts of total rainfall should be adjusted downward to represent synoptic patterns.

As Flossy slowly moved across southern Georgia to the South Carolina border on September 26, the general size of the area of heavy rains (fig. 11) remained relatively the same despite the fact that the source of moist tropical air responsible for the precipitation was being cut off as the cold air entered the circulation from the west. The extension of the quasi-stationary polar front into the storm center may be a partial explanation. According to Petterssen [9], when the orographic upglide is superimposed upon the general frontal upglide, there is a consequent increase in the rates of condensation and precipitation. This added lift given to the overrunning air could have been enough to compensate for any deficiencies in the moisture content and temperature of the modifying tropical air mass.

After Flossy became extratropical, although the whole general area approximately 150 miles to the north of the Low had precipitation amounts in excess of 1 inch per 24 hours, only those regions on the eastern slope of the Appalachians had totals of 3 inches per 24 hours (figs. 11

and 12). The rate and hence the total amount of precipitation depended largely upon the strength of the flow of the moist unstable air mass normal to the mountain barrier. This capacity to produce heavy rains became more evident with time as the easterly flow north of the center and normal to the mountains steadily increased. The resulting friction and cross-isobaric flow along the windward side of this range caused convergence and ascending vertical motion, which in turn enhanced the rainfall intensity. Conversely, the divergence and descending motion on the leeward side resulted in little or no precipitation in those areas west of the higher mountain ridges.

On the following days, September 28 and 29, as the cyclone filled and moved more rapidly northeastward reducing the onshore flow, the rainfall totals tapered off. Figure 13 shows a one-inch isohyet in the vicinity of Washington D. C. just barely larger in size than the 3-inch area of the previous 24-hour period. On September 29, with the gradient along the New England coast more significantly lessened, precipitation totals fell off sharply (fig. 14). Only isolated coastal stations reported amounts in excess of one-half inch in 24 hours, most of which occurred in the first 12-hour period.

7. DESTRUCTION

From the time Flossy approached the United States until the time it moved out over the Atlantic, it left in its wake widespread damage from hurricane-force winds, high tides, and heavy rains. Above normal tides and heavy wave action battered the Gulf Coast from west of Grand Isle, La., to Tampa, Fla., and windblown sand along the beach areas drifted on highways [13]. As the storm moved over southwestern Georgia, the high winds and heavy rainfall damaged unpicked cotton and unharvested corn to the extent that while the crops were not entirely lost, the quality was greatly reduced. Of course, property damage such as unrooted trees, broken branches, and broken TV antennas was extensive but relatively minor.

Along the Atlantic Coast, damage was restricted to flooding caused by the strong onshore winds ahead and east of the storm center producing above-normal tides and wave action. However, residents of these areas were notified of the predicted high water and personal losses were reduced considerably.

In spite of the destruction left in her path, Flossy was not entirely detrimental. The heavy precipitation associated with the storm greatly relieved the drought conditions in northern Florida, Georgia, and the Carolinas. The value of these beneficial rains may even outweigh the total damage.

ACKNOWLEDGMENTS

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